Asian J. Energy Environ., Vol. 5, Issue 4, (2004), pp. 223-266

Clean Energy Conversion from Waste Fuels Using High Temperature Air Combustion Technology

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(Received : 15 June 2003 – Accepted : 1 January 2004)

Abstract : Recent advances on High Temperature Air Combustion (HiTAC) are reviewed. In HiTAC method, combined heat regeneration and low oxygen methods are utilized to enlarge and control the flame thermal behavior. The HiTAC technology emerged from the conception of Excess Enthalpy Combustion (EEC). This technology has the potential for very wide applications, including power and process industries and energy conversion. The technology has been shown to provide significant reduction in energy consumption (up to 60%), downsizing of the equipment (about 30%) and lower emissions (about 30%) while maintaining high thermal performance of the system. Energy savings translate to reduction of CO_2 and other greenhouse gases to the environment.

Qualitative and quantitative results are presented on several gaseous diffusion flames using high temperature combustion air. A specially designed regenerative combustion test furnace facility, built by Nippon Furnace Kogyo, Japan, was used to preheat the combustion air to high temperatures. The flames with highly preheated combustion air were much more stable and homogeneous (both temporally and spatially) as compared to the room-temperature combustion air. Information on global flame features, flame spectral emission characteristics, spatial distribution of OH, CH and C^2 species and emission of pollutants has been obtained. The global flame feature showed a range of flame colors (yellow, blue, bluish-green, green and purple) over the range of conditions examined. In some cases hybrid color flame was also observed. Under certain conditions, flameless or colorless oxidation of the fuel has also been observed. Low levels of No_x along with negligible amounts of CO and HC have been obtained under high temperature air combustion conditions. The thermal and chemical behavior of high-temperature air combustion flames depends on fuel property, preheat temperature and oxygen concentration of air. Flames with high temperature air provide much higher heat flux than normal air.

The challenge associated with wastes and low -grade fuels is that their composition varies both temporally and spatially. The high temperature air combustion technology has been successfully utilized to convert wastes and low - grade fuels to low and medium heating value clean gaseous fuels. The gaseous fuel is of uniform composition and does not result in the emission

of harmful pollutants that are often generated from the incineration of wastes. Opportunities provided by this technology for use in other areas are presented. Challenges of this new emerging technology for different applications are also discussed.

Keywords : High temperature air combustion technologies, Energy savings, Clean energy conversion from wastes, Pollution reduction.

Introduction

The principle conception of Excess Enthalpy Combustion was presented almost three decades ago 1]. In excess enthalpy combustion the thermal energy released is fed back to the fresh reactants so that the temperatures obtained with excess enthalpy combustion are much higher than its counterpart with normal temperature air. However, in High Temperature Air Combustion (HiTAC) the maximum temperature in the reaction zone is held constant by utilizing diluted combustion air having low oxygen concentration. This low oxygen concentration air is obtained by recirculating part of the combustion products into the incoming combustion air. The air is preheated to temperatures in excess of 1000°C, depending on the application. Most of the previous research activities have been focussed on gaseous fuels, such as methane, propane, LPG, process gases [1-9]. The HiTAC technology has significant potential for utilizing various kinds of gas, liquid, solid and waste fuels for applications to many industrial, power systems and processes [10-34].

Combustion research has always been concerned with meeting various industrial, societal and military demands. An example of this can be seen from the origination of HiTAC concept. Global environmental problems, including not only acid rain, particulate and ozone layer destruction, but also global warming from greenhouse gases, such as CO_2 and methane, which are recognized to cycle between atmosphere and the earth. Furthermore, the fossil fuel shortage of the 1970's, although it could have delayed to some extent, is of serious concern for its recurrence by both the users and the technical community. Therefore, simultaneous requirements of both environment protection and energy conservation require rapid development of combustion science and technology for various applications. The science and technology of combustion has made significant progress during this century, in particular after World War II. HiTAC technology has shown the best potential for energy conservation, reduction of pollutants generation, and better quality of products for a range of applications [10].

In this paper, recent progress on HiTAC is first reviewed. Qualitative and quantitative data on several gaseous fuels using high temperature combustion air are presented. Information is also presented on the use of this technology for cleaner conversion of wastes to gaseous fuels. The major emphasis is placed on the following:

- Basic research for determining the flame structure
- Use of gaseous fuels, such as CH_4, C_3H_8, LPG, CO, H_2, and C_2H_2

- Laboratory scale investigations
- Highly preheated air having different levels of oxygen concentration (By diluting the air with non-oxidative gas, such as, N_2 and CO_2)
- Formation and emission of pollutants, including NO_x
- Conversion of different types of wastes to cleaner fuels

It is to be noted that significant differences exist when the dilution gas is changed form N_2 to CO_2. In addition several other issues are also of interest, such as, flow field, temperature distribution, mixing, combustion stability, flame emissivity and heat flux. Information is presented here on some of the above quantities. After brief description on the report outline, description of highly preheated air combustion (HiTAC), including the concept of excess enthalpy combustion, is provided. The motivations and objectives of HiTAC are discussed so that the relationship between environmental issues and energy conservation can be clarified. Recent research progress on HiTAC in laboratory scale are then discussed which has, for most part, been centered on determining the structure of flames under various input and operational conditions. Some experiences from field trials are also given. The specific focus has been on the following:

- Heat transfer enhancement, which is affected by mean temperature distribution and temperature fluctuation.
- Flow field, which affects the main motion of flame and the flame volume occupied.

- Reaction mechanisms, which may be responsible for flame appearance, presence of chemical species, flame structure and pollutant formation and emission.

Research methodology as well as results from the experimental studies are provided, including global flame features and stability, NO_x emission and distribution of various chemical species within the flames. Several aspects on the practical applications of HiTAC are then addressed. The flame structure in practical industrial systems, when available, is also discussed. Some considerations on challenges of this technology are then provided. It is to be noted that whenever comprehensive ongoing processes in a flame are to be investigated, emphasis should be placed on the coupled effects between several quantities so that one can understand the interactions between two or more quantities.

1. Motivation and objectives of HiTAC

1.1 Motivation of HiTAC

Fossil fuels, such as, coal, oil and natural gas, have been used by society for thousands of years. These fuel sources have never been considered exhaustible until this century. Rapid growth of human society and industrialization has resulted in rapid utilization of natural resources on the earth. This then leads to our concern that in the very near future the fossil fuels, which encompassed our main energy consumption cycle, will run out. These considerations were mainly strengthened during the energy crisis of the 1970's. Although nuclear and solar energy may provide more promise for the future, fossil fuel can not be quickly replaced for all applications, at least in the near future because of their several advantages including non-radioactivity, safety, mature utilization technologies, high conversion efficiency and cost effectiveness. However, when one considers the negative impact of fossil fuels, besides the limited reserves, concerns over environmental issues is quite serious.

In this century more and more attention has been given to fossil fuel utilization because of the problem of pollutants emission into the atmosphere. Pollutants such as CO, CO_2, NO_x, hydrocarbons, soot and particulate, metals, polycyclic aromatic hydrocarbons, dioxins have been on the priority list. The emissions of CO_2 and methane greenhouse gases are directly responsible for global warming.

In 1992, the United Nation Conference on Environment and Development (the Earth Summit) provided global efforts to protect our environment. At the Kyoto protocol in 1997, efforts of many developed countries to reduce carbon emissions by 7% below the 1990 level over the next 10 years were discussed. High Temperature Air Combustion provides potential opportunity to achieve this goal, at least in certain sectors of energy consumption.

Thermodynamic considerations suggest that high temperature combustion air increases flame temperature, combustion intensity and efficiency, and heat transfer. However, with the usual air preheat NO_x will also increase. Controlled combustion can reduce NO_x emission as well as other pollutants. Our focus therefore should be on reducing both energy consumption and pollutant formation and emission.

HiTAC is one of the most promising combustion techniques that attempt to solve such problems, especially to satisfy the present conflicts between energy savings and pollutant formation and emission. HiTAC is particularly attractive for processes requiring uniform temperature distribution and heat flux in the chamber. Controlled flame behavior can result in uniform thermal field, low combustion noise and emissions, and smaller chamber size for processing the same material or increasing productivity for the same furnace size. However, in order to explore further the full potential of highly preheated air combustion, one must examine in detail the structure of the highly preheated air flames over a wide range of conditions and different fuels.

1.2 Objectives of High Temperature Air Combustion (HiTAC)

1) Energy Saving

High-temperature air combustion technology uses high quality heat regenerative media as heat exchanger, for example, ceramic honeycomb or balls, which provides energy storage. Ceramic honeycomb is better than balls as this provides high surface area, low-pressure drop and high efficiency. One of the major heat losses from most industrial furnaces and processes is from the exhaust gases. The regenerative media used in the HiTAC devices recovers a large amount of thermal energy from the exhaust gases, which translates to fuel saving in the combustion process. In addition the heat flux from HiTAC flames is much higher than their counterpart. In the 'High Performance Industrial Furnace Development' project, the objective was to demonstrate significant energy savings (about 30%) using regenerative media, down sizing of the equipment by about 25% and pollutants reduction (including CO_2) by about 30% [2]. This goal has been successfully demonstrated in Japan via several field trial demonstration projects [19-21]. The HiTAC provides uniform thermal field and hence a better product quality product from the process.

2) CO_2 Reduction

The role of CO_2 in global warming phenomena is now widely recognized. The demands for reducing CO_2 emission are higher than ever before. All fossil fuels generate CO_2 as a byproduct so that any efforts to reduce energy consumption will result in a reduction of CO_2 emission. Good correlation between fuel consumption and CO_2 production suggests that CO_2 reduction should be about the same as energy saving from the HiTAC technology.

3) NO_x Reduction

Emission of NO_x has been recognized to be responsible for the destruction of the ozone layer in the upper atmosphere. NO_x (NO, NO_2, N_2O, N_2O_4, N_2O_5, etc.) involves the complicated reaction mechanisms, which result in accelerating the ozone depletion in the oxygen cycle on earth. Therefore, combustion engineers have focussed their attention to develop various strategies to reduce NO_x emission and improve the combustion process. HiTAC is one of the most advanced techniques because of low levels of NO_x formation and emission [19-21, 25-29].

4) Reduction of Equipment Size

Studies on HiTAC flames show superior thermal field uniformity and uniform heat flux distribution as compared to combustion with normal temperature air [1314]. The ignition delay time is different as compared to room temperature air [58]. This suggests that industrial equipment has greater potential of reduced size and hence material conservation with high temperature combustion air [15,21].

Simultaneous realization of the above benefits was considered impossible before. The unique flame features associated with HiTAC flames provide greater potential of this technology for a wider range of applications [10,25]. Some examples include fuel reforming, power generation, waste destruction and chemical processes.

2. Basic principle of HiTAC

2.1 Thermodynamic consideration of combustion process

Flame temperature is one of the important factors when considering combustion efficiency and energy conversion efficiency. Weinberg [1] provided the initial concept of Excess

Enthalpy Combustion in 1971. In his study, limitations on combustion temperature were discussed, including both positive and negative factors associated with combustion temperatures in a certain range. Heat circulation or exhaust gas circulation regime, using high-efficiency heat exchanger, was adopted in order to increase the combustion temperature and associated energy savings. However, combustion engineers have to pay attention to the upper limit of combustion temperature because of materials constraints used in the equipment and/or pollutants formation. Various possibilities on enthalpy intensification were described [2]. From the economic point of view, it is of course better to use thermal energy generated by the combustion process itself to heat-up the oxidant or fuel, which is often of low thermal energy, than via the use of electrical or mechanical energy.

The amount of combustion-generated energy circulated into the combustion process is given by [1]:

$$\overset{T_1}{\underset{T_0}{}} C_p dT = Q_c + Q_a = H_t - H_0$$

where, T f is the final temperature, T 0 is the initial temperature, Q_c is the heat released by chemical energy conversion, Q_a is the energy added, Ht and H0 are the enthalpy at two states. The circulation part of thermal energy from combustion generated products will increase the combustion temperature so that enthalpy of the reaction zone will be above the conventional combustion level. This has resulted in the use of the term called “Excess Enthalpy Combustion”.

Increase in thermodynamic efficiency must be coupled with other desirable characteristics of low NO_x formation, reliability of the refractory material, distribution of temperature, and other associated factors. None the less the heat circulation and excess enthalpy methods throw some light on the next generation of advanced energy conversion technology and combustor design. This method provides some idea for controlling the combustion temperature, independently of the fuel composition and simultaneously satisfying the demands of high combustion intensity, reduced pollutant formation from fuels of any composition, including low -grade fuels.

2.2 Basic design strategy of Excess Enthalpy Combustion

Generally, Excess Enthalpy Combustion can be realized by internal or external circulation or by some suitable combination of both, if heat circulation strategy is adopted for combustion improvement [25]. Most designs of internal heat circulation have involved bluff body, porous media or swirling flow. Most of these have been aimed at flame stabilization [16] and are very effective. However, with the increased concern on pollutant reduction and energy conservation advanced methods are being sought. Internal heat circulation relies on heat convection and species circulation so that a pool of hot and active radicals in the reaction zone can be maintained which subsequently assists in flame stabilization. In contrast to internal recirculation method, external circulation methods use a heat exchanger to transfer the thermal energy via conduction between combustion products and solid media so that heat can be exchanged to the cool reactant [1]. Most of the enthalpy contained in hot combustion products can be recirculated back to the combustion process. This then allows one to utilize the energy for flame stabilization, control the reaction process and achieve desirable composition in addition to conserving energy.

2.3 Implementation of Excess Enthalpy Combustion in HiTAC

Thermodynamic considerations suggest that preheating the oxidant (and not fuel due to possible fuel decomposition and safety aspects) to very high temperatures will increase thermal cycle efficiency. Thus, enthalpy will be added into the flame with air preheat without any other changes. From the point of pollutant formation, especially NO_x, high temperature of combustion has been recognized to be one of the most important parameters. Therefore, the combustion temperatures and chemistry must be controlled so that NO_x formation and emission is acceptable. One method of maintaining the same temperature in the combustion zone is to dilute the incoming combustion air with hot combustion products. The recirculation of hot products into the reaction zone will dilute the inlet concentration of oxygen in the combustion air. This alleviates the presence of peak flame temperatures, which subsequently helps to reduce the NO_x emission levels. Further examples of such depiction can be found in refs. [2, 4, 17, 20].

Efforts made by Nippon Furnace Kogyo Kaisha Ltd. (NFK) starting from the early 1990's, under the leadership of late President Ryoichi Tanaka, were focused on efficiency and pollution from furnaces and boilers. Their goal was to reduce emissions (by 10-30%), save energy and increase furnace efficiency (by 10-30%), and reduce the size of the equipment (by 10-25%) using regenerators and excess enthalpy principles. In the North American design, ceramic balls were used in the regenerator to preheat the combustion air with gases exiting from the furnace. The use of ceramic balls in a packed bed provided much higher temperatures of the combustion air. These temperatures were much higher than those achieved previously by recuperators. In the NFK High Temperature Air Combustion (HiTAC) technology a honeycomb regenerator is used. The honeycomb regenerator is much more compact than a bed packed with ceramic balls, has high specific surface area, low thermal inertia and provides a very low pressure drop [2,15]. In the HiTAC technology low oxygen concentration air at high temperature is used for the combustion air. In conventional burners increasing the air preheat temperature increases NO_x emission levels. However, in high temperature air combustion, the temperature of combustion gases in the furnace or reactor is small (only about 50 to 100°C above the incoming combustion air at high temperature). The oxygen concentration in the combustion air is very low (only about 2 to 5%, depending on the application). Under these conditions the hot spot zones are eliminated to provide uniform thermal field distribution in the combustion zone with high temperature combustion air [14]. The peak temperatures in the combustion zone are suppressed to result in very low NO_x emission levels. The heat flux from the flame with high temperature combustion air is also very high [13, 14, 25].

A schematic diagram of the conventional flame, high temperature air flame and HiTAC flame as well as the distribution of heat flux is shown in Fig. 1. Major thrust in all kinds of furnaces used in boilers, melting, reheating, soaking, heat treatment is to reduce production costs and improve product quality. Fuel costs represent a major cost element in furnace operation. Furthermore, the furnace design must also offer reduced pollution. Treatment of exhaust gases to reduce pollutant emission is not desirable as this increases the capital investment in addition to the added equipment maintenance. High temperature air combustion provides all of the above benefits.

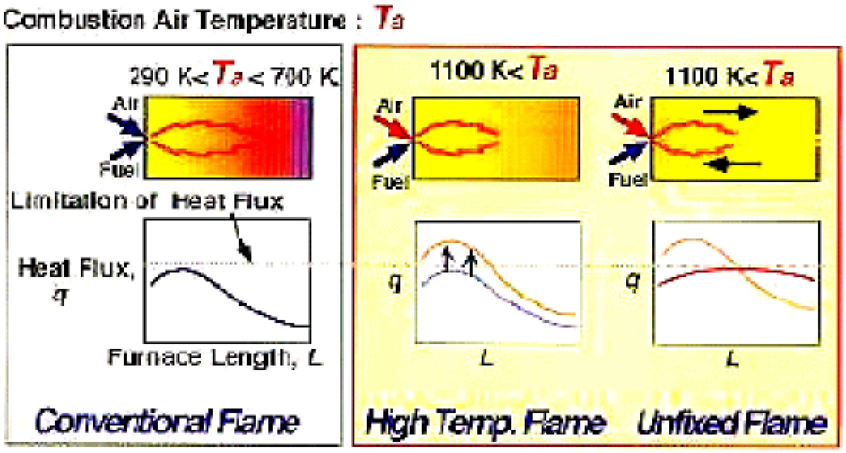


Figure 1. A Schematic diagram of flame and heat flux distribution in a furnace with low temperature combustion air, high temperature air, and high temperature and low oxygen concentration combustion air (HiTAC) conditions.

Most of the studies have been carried out on gaseous fuels (LPG, propane, methane and low heating value gases). Recently, some studies have also been carried out on heavy fuel oil [18], light oils [12] and solid-waste fuels [11]. The fundamental studies provided an insight on the thermal, chemical and fluid dynamical behavior of the flames [17, 20] while the applied research provided optimal utilization of the technology for some specific application, e.g., heating, melting, heat treatment, soaking, boiler [19-21, 28].

3. Flame Characteristics with High Temperature Combustion Air

3.1 The experimental facility

A high temperature air test furnace facility, developed and built by NFK, Japan, has been used to determine the features of HiTAC flames, see Figure 2. The facility consists of two burners, each firing in furnace section A and B. It consists of two main components. The furnace has two combustion chambers; each equipped with a ceramic honeycomb regenerator at upstream section of the respective burners. The other component is the computer control unit with flow and switching sequence controllers. Further details on this test facility are given in ref. 2. When the burner in the furnace section A is firing, heat-up fuel at ambient temperature is supplied to burner A. Combustion air gets heated up while passing through the regenerator located downstream of the furnace section B. Furnace gases in chamber B are, therefore, directly drawn by regenerator B to store heat. The exhaust gases, after passing through the regenerator, are released to the environment via a 4-way-valve. After prescribed time duration (about 30s) the system is switched so that the burner in chamber B is firing and the regenerator located upstream of the furnace section A gets heated. The above process is repeated again with the burner A firing while the regenerator B is heating up. By repeating this cycle several times, more and more heat is stored in the regenerators. When the desired temperature of the regenerator is achieved the air is passed over the regenerator. The air gets heated to the desired high temperature. The air with this facility can be heated to temperatures close to the furnace temperature. The test fuel is then introduced into section A of the furnace.

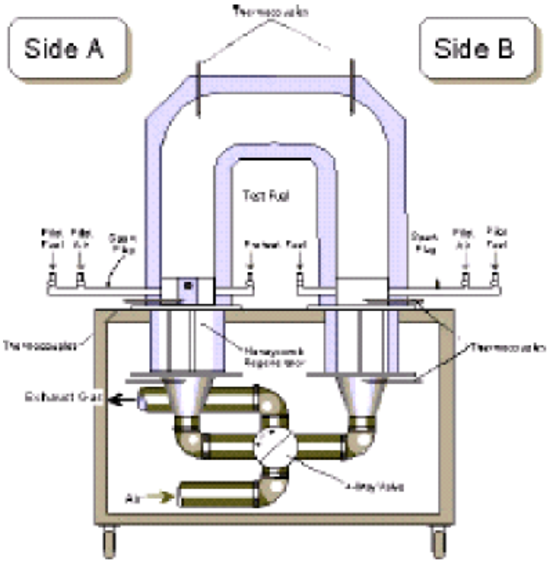


Figure 2. A schematic diagram of the experimental high temperature air test facility.

3.2 Flame characteristics

The flame characteristics are then examined with the high temperature combustion air using several advanced diagnostics. The stability limit of propane flame as a function of air-preheat temperature and oxygen concentration in air is shown in Fig. 3. The flame stability limits increases significantly at high temperatures and low oxygen concentration. Under HiTAC conditions the flame stability is very wide as compared to any other combustion method.

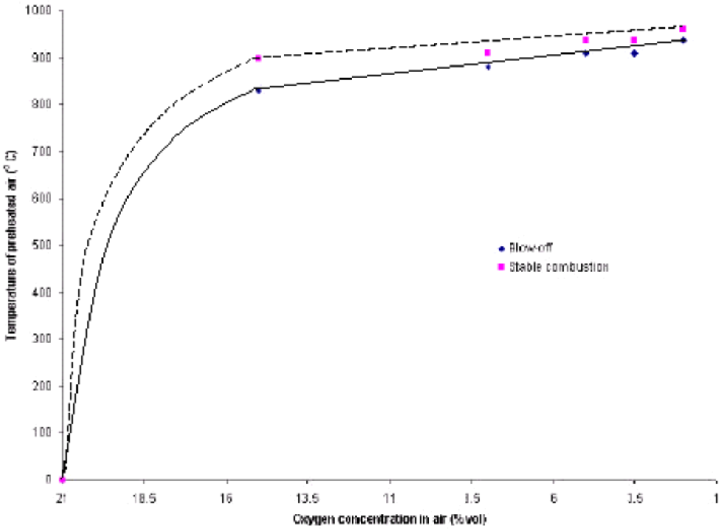


Figure 3. Stability limits of the propane flame as a function of air preheat temperature and oxygen concentration in air.

The flame structure was found to depend on fuel property, preheated air temperature and oxygen concentration in the air. The diagnostic facility used here includes direct photography, spectrometer, flame signatures using narrow band filters and ICCD camera for OH, CH, C_2, and gas analyzers for NO_x, CO,

CO_2 and hydrocarbons. In this paper experimental data on several gaseous nonpremixed flames are presented using high temperature combustion air.

The regenerator can preheat the incoming air to temperatures of about 1200°C. Furthermore, it is possible to dilute the air with any gas or the combustion products using simulated exhaust gas recirculation (EGR). The fuel was injected via a nozzle (about 1 mm diameter) in a direction normal to the heated airflow so that the initial mixing between the fuel and air is in the form of a jet in a cross flow. This form of jet mixing is known to be very efficient. The momentum of the gas jet was maintained constant when examining other gaseous fuels. This provided similarity in mixing between the fuel and air. Oxygen concentration in the air was varied from 21% (normal air) to below 2%. Thus the equivalence ratio was varied from $\approx$ 0.83 (with 2% O2) to $\approx$ 0.079 (with 21% O_2) for the propane-air flames examined here. The equivalence ratio was, therefore, different between fuels for the same oxygen concentration. As an example, changing the fuel from propane to methane and maintaining the same momentum of the fuel jet changed the equivalence ratio to 0.3 (for 2% O_2 in air) and 0.03 (for 21% O_2).

The combustion air supplied to the test section of the furnace was preheated to temperatures ranging from 900°C to 1200°C with oxygen concentration ranging from 21% to 2%. Flame photographs were obtained with a 35-mm camera using very short exposure times. From the flame photographs the flame color and flame area were analyzed using a computer program. Flame photographs with air preheat temperature of 1100°C and oxygen concentration of 21, 8 and 2% in combustion air are shown in Figure 4 (corresponding to N of 0.079, 0.21 and 0.83 respectively) using propane as the fuel. The flames showed four distinct colors of yellow, blue, bluish-green, and green, see Fig. 4. Under certain conditions colorless flame (flameless oxidation of fuel) was also observed [22]. The green color observed for propane flames at low oxygen concentration and high airpreheat temperatures has not been observed for methane flames over the range of conditions examined [3,10,12,22]. This suggests significant role of fuel property on the flame thermal signatures and heat transfer characteristics of flames.

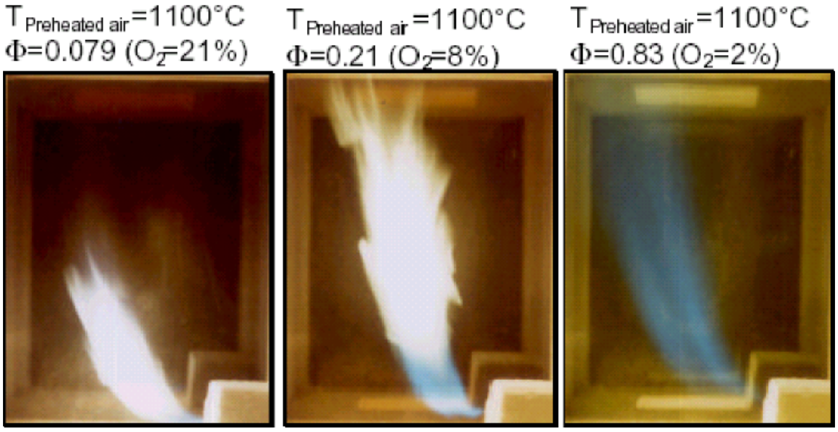


Figure 4. Propane flame photographs with combustion air temperature of 1100°C and O_2 conc. (from left to right) of 21%, 8% and 2% (nitrogen as the dilution gas).

The size and color of the flame depends on air preheat temperature and oxygen concentration (obtained, for example, by changing the amount of gas recirculation) in the combustion air. All flames showed a unique structure as the air-preheat temperature was increased and the oxygen concentration was reduced from 21% to 2%. The flame volume was found to increase with increase in air temperature and decrease in O_2 concentration in the combustion air. At any fixed temperature, the total flame size decreased with increase in oxygen concentration from 2% to 21%. No yellow color flame was found at temperatures below 950^{o}C and oxygen concentrations below 15%. The size of blue color region in the flame decreased with increase in oxygen concentration (up to about 15%) and temperature. Between 900^{o}C to 950^{o}C and O_2 concentrations between 5 to 15% all flames were of blue color. For very fuel-lean mixtures and at high air preheat temperatures (1100^{o}C), the luminosity of the flame (and hence the heat flux) was found to be very high. Further discussions on flame features are given in refs. 3, 10 and 21.

At high air preheat temperatures and low oxygen concentration, e.g., around 2 - 5 % oxygen concentration in air, the flame was found to be of greenish color. The greenish flame color is pronounced at higher air preheat temperatures and low oxygen concentration in the air. This suggests high levels of C_2 species (swan band) from within the flames under these conditions. The results also show that the flame volume dramatically increases under conditions of low oxygen concentration and high temperature combustion air, see Fig. 4.

No flame color could be observed with at very low O_2

concentration in air (less than 2%). We postulate this condition to be flameless oxidation of fuel (also called FLOX or colorless oxidation of fuel). Determination of pertinent species present under flameless oxidation conditions will allow one to postulate the mechanistic pathways. The fuel chemical property has a significant effect on the flameless oxidation of fuel [3, 21-23, 29]. The thermal and chemical behavior of flameless oxidation requires further examination.

The increase in green color for propane flames, obtained by using a computer program sensitive to the color in the flame photographs shown in Fig. 4, as a function of oxygen concentration in air and air preheat temperature is given in Fig. 5. This program allowed determination of flame length and volume associated with different colors in the flame under various operational conditions. The total yellow flame volume increases with increase in O_2 concentration in the air. The increase in flame temperature increases the yellow fraction of the flame at high O_2 concentrations over the range of temperatures examined. The flame volume associated with green color of the flame increases sharply at O_2 concentrations less than 5% in the combustion air as shown in Fig. 5. Similarly the flame volume associated with other colors in the flame can be determined. The flame radiation associated with different colors is very different. In some applications high radiant flux is desired while for other applications it is undesirable. The information presented here, therefore, assists in providing design guidelines on the use of High

Temperature Air Combustion (HiTAC) technology for various applications.

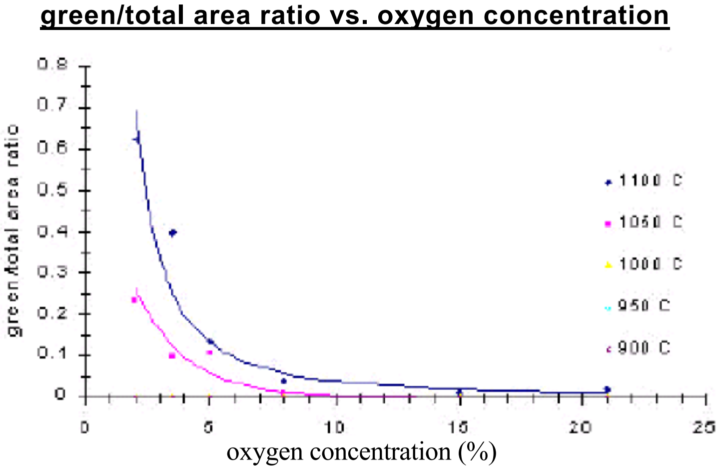


Figure 5. Variation of green flame/total flame volume with O_2 concentration in air and air preheat temperature for the propane flame.

3.3 Emission spectra

The spatial distribution of C_2, OH and CH from within the flames, obtained using a ICCD camera having transmission at the appropriate band for the specie, showed significant effect of oxygen concentration and air preheat temperature on the distribution of above species in flames [3,5]. At high air preheat temperatures and low oxygen concentration [3,5] the propane flame had two high regions of C_2 concentration, both regions being near to the upstream portion of the flame. With increase in oxygen concentration the flame structure became more symmetrical. It was observed that flame fluctuations were negligible at high temperature and low oxygen concentration in the combustion air

[4,14,17]. Quantitative data on flame fluctuation at high air preheat temperatures and low oxygen concentrations are given in refs 23 and 24. Temperature fluctuation under high temperature air conditions has been provided in refs. 14, 20, 25. The measured temperature fluctuations were very low even at higher frequencies.

In order to determine the important chemical species present under High Temperature Air Combustion (HiTAC) conditions, emission spectra of the flames under different operational conditions have been determined at selected positions in the flames. Sample results with 4% O2 concentration and air preheat temperatures of 970, 1030 and 1100^{o}C taken at one location in the flame (X = 3 cm and Y = 1.5 cm) are shown in Fig. 6. These results correspond to simulated exhaust gas recirculation (EGR) of 426%. These results were obtained using a spectrometer by scanning the flame in 100 nm wavelength intervals so as to enhance the resolution. Thus, one flame condition required 5 scans to scan between 250-750 nm. No significant species were found beyond 750 nm for the examined flames. The results show a significant increase of OH, CH, C_2 and H2O emissions with increase in air preheat temperatures. The relative amount of various species present at various positions in the flame was different. Global observations of the flame showed that increase in air preheat temperature at low oxygen concentration changes the flame color from blue to bluish-green with. This suggests an increase in the emission of C_2 radicals. At 516.5 nm the increase factor is 1.9 from 970^{o}C to 1030^{o}C and 2.4 from 970^{o}C to 1100^{o}C. Similar results were found for other species [5]. The green color of the flame is directly attributed to the increase of C2 (swan band) emission. Further downstream of the flame negligible amounts of CH and C_2 species were detected.

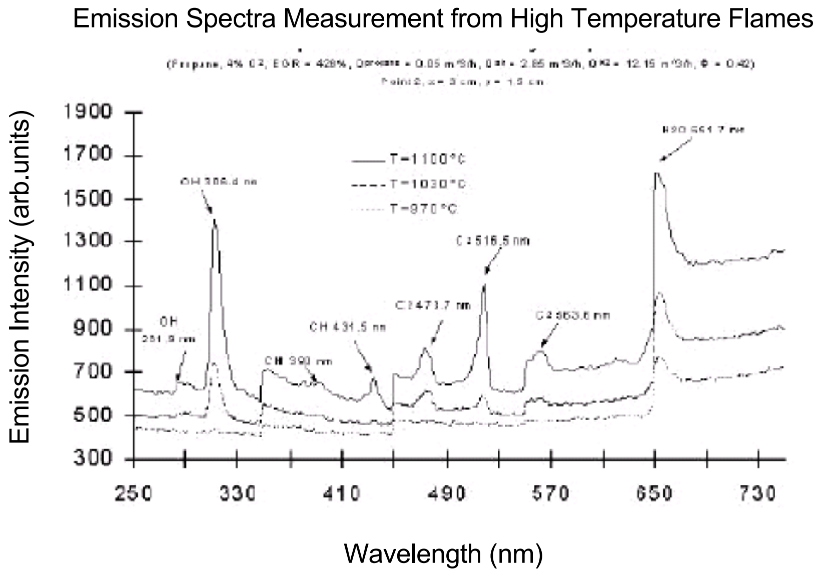


Figure 6. Flame emission spectra at one point in the propane flame (x=3cm and Y=1.5cm) for three air-preheat temperatures (nitrogen as the dilution gas).

3.4 NO_x emission

In order to determine whether high temperature air combustion (HiTAC) would adversely affect the emission of NO_x and other greenhouse gases, measurements were made on the emission of various gaseous species. Figure 7 shows the NO_x emission levels for propane flame as a function of air preheat temperature at 15%, 8 and 2% O_2 in air. The emission of NO_x increases with air-preheat temperature. However, at high air preheat temperatures and low oxygen concentration very low NO_x emission is observed. NO_x emission at 1150°C air preheat temperature decreased from 2800 ppm at 21% O_2 to 40 ppm at 2% O_2. The emission of CO and UHC was negligible. Similarly the emission of NO_x was fund to be low with CO as the fuel, see Fig. 8. The emission of NO_x was low under HiTAC conditions of low oxygen concentration and high airpreheat temperature. Both fuels provided negligible amounts of hydrocarbons. The measured HC is attributed to the measurement location of the probe and fuel switching cycle.

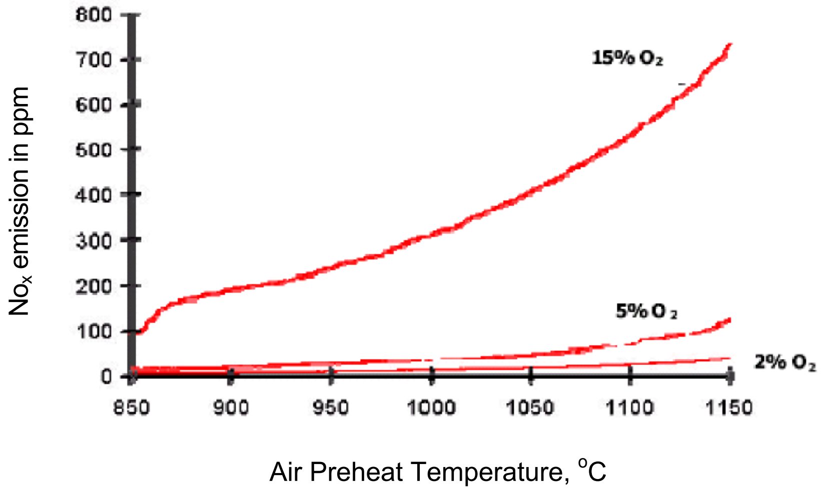


Figure 7. Emission of NO_x as a function of air-preheat temperature and O_2 concentration in air using propane as the fuel (nitrogen as the dilution gas).

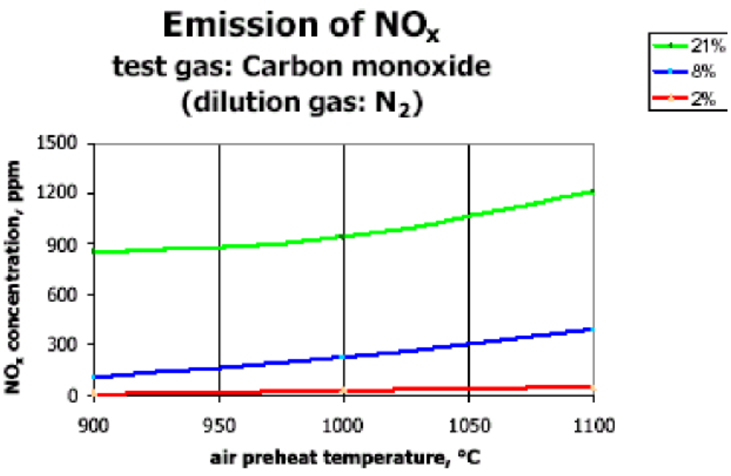


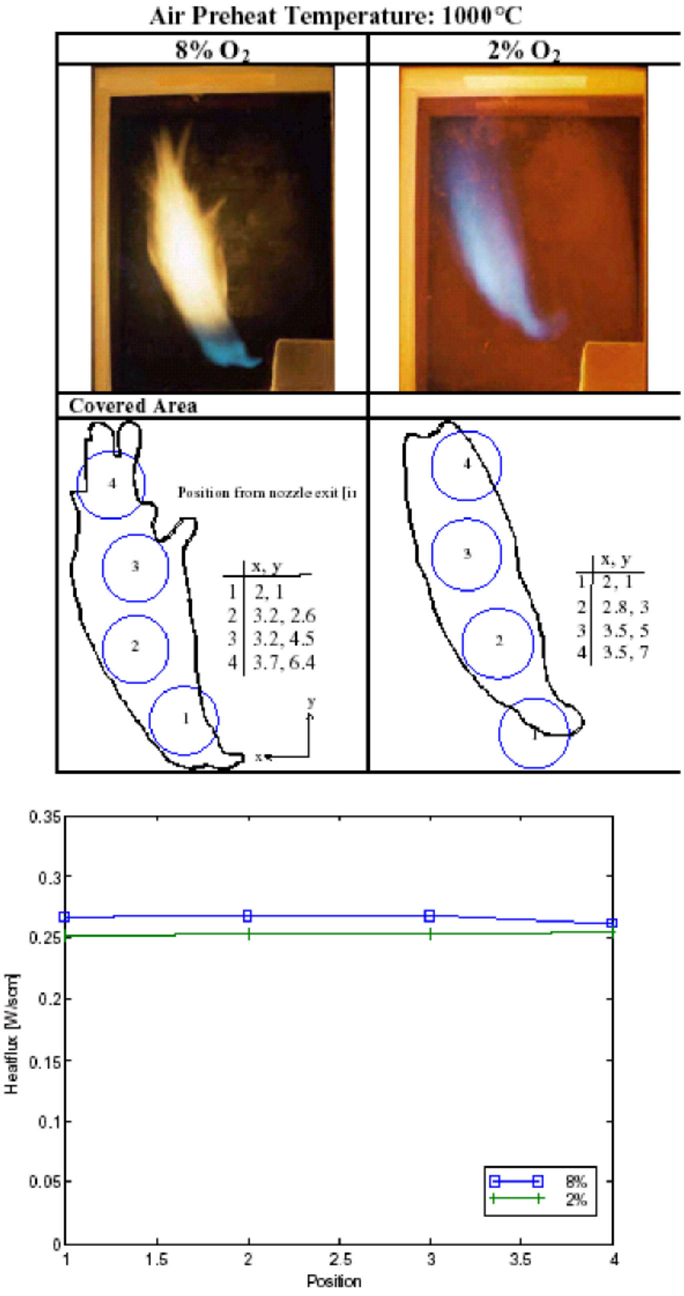
Figure 8. Emission of NO_x as a function of air preheats temperature and O2 concentration in air using carbon monoxide as the fuel (nitrogen as the dilution gas).

3.5 Heat Flux Distribution

The uniformity of heat flux distribution from within the flames was determined for a range of experimental conditions using various fuels. The variation of heat flux along the flame for three O_2 concentrations of 21%, 8% and 2% is given in Fig. 9 for the propane fuel. Similar trend was found for the other fuels. The corresponding flame photographs and the measurement locations are also shown in the figure. The results show very uniform heat flux distribution from the flames. The magnitude of the actual value of heat flux at each position in the flame may not be accurate, as the measured results require calibration. Nonetheless, the distribution of the heat flux in the flame will remain unchanged. The results were also obtained with normal air temperature and O_2 concentration. The heat flux distribution was found to be a bell shaped curve, having low value near to the burner exit, peaked downstream and then decayed further downstream from the burner exit. Furthermore, the absolute value was much lower than that found for the HiTAC flames. It can, therefore, be concluded that the heat flux from flames with high-temperature air is much higher and uniform. This can be translated to uniform heating of the material to be heated and reduced energy requirement.

3.6 Effect of fuel property on global flame characteristics

Several different fuels have been examined to determine the effect of fuel property on the flame characteristics. Sample results with methane, hydrogen and acetylene fuels, using N_2 and CO_2 as the dilution gas, are given in Figs. 10, 11 and 12, respectively. Two different gases for diluting the concentration of O_2 in air are nitrogen and CO_2. In all cases the fuel jet momentum was the same as that for the propane fuel. This provided the jet similarity to yield similar mixing patterns. The flame features of methane and acetylene are much different than those observed for propane flames. The results also show that the dilution air significantly affects the flame features. In all cases a larger flame volume is observed under HiTAC conditions.



	x, y
1	2, 1
2	3.2, 2.6
3	3.2, 4.5
4	3.7, 6.4

	x, y
1	2, 1
2	2.8, 3
3	3.5, 5
4	3.5, 7

Figure 9. Heat flux variation along the flame using propane as the fuel, Tair = 1000^{o}C (sensor at 6.5 inches from the center axis of the flame).

The results showed flameless oxidation conditions under low oxygen conditions using methane as the fuel. Both the fuels provided no evidence of the presence of green color flame for the range of conditions examined. Purple color flame was observed with hydrogen fuel under certain conditions (15% O_2). This suggests that fuel properties have significant effect on the combustion mechanism. Flameless oxidation with methane as the fuel has also been observed [3]. Measurements on the flame spectra with methane fuel showed no peaks at the swan band. Global flame characteristics can assist one in deciding the detailed diagnostics on the flames.

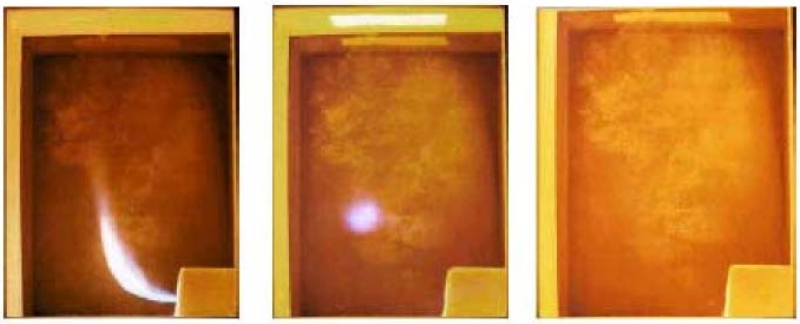


Figure 10 (a). Methane flame photographs with combustion air temperature of 1000°C and oxygen concentrations (from left to right) of 21%, 8% and 2%, respectively (nitrogen as the dilution gas).

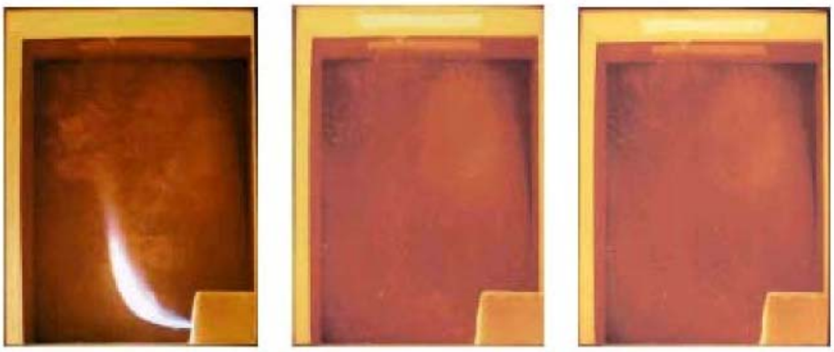


Figure 10 (b). Methane flame photographs with combustion air temperature of 1000°C and oxygen concentrations (from left to right) of 21%, 8% and 2%, respectively (carbon dioxide as the dilution gas).

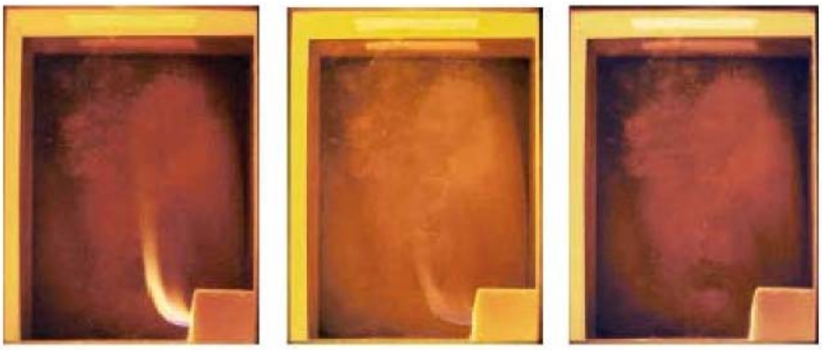


Figure 11 (a). Hydrogen flame photographs with combustion air temperature of 1000°C and oxygen concentrations (from left to right) of 21%, 8% and 2%, respectively (nitrogen as the dilution gas).

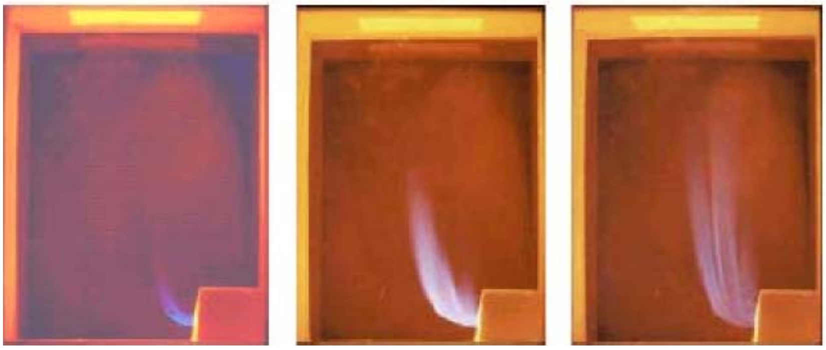


Figure 11 (b). Hydrogen flame photographs with combustion air temperature of 1000°C and oxygen concentrations (from left to right) of 15%, 5% and 2%, respectively (carbon dioxide as the dilution gas). UV film was used for the 15% O2 case.

Figure 12(a). Acetylene flame photographs with combustion air temperature of 1000°C and oxygen concentrations (from left to right) of 21%, 8% and 2%, respectively (nitrogen as the dilution gas).

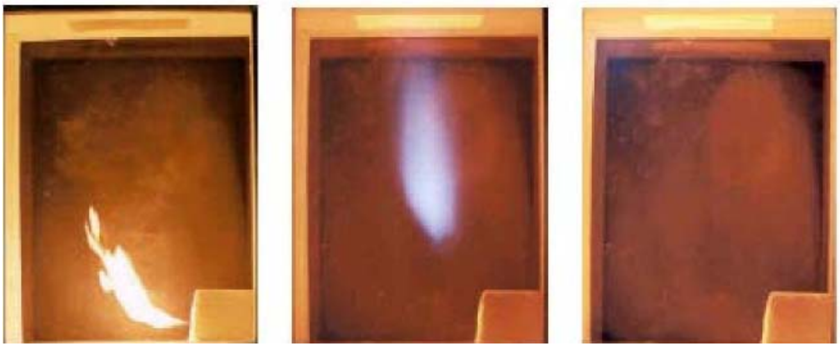


Figure 12(b). Acetylene flame photographs with combustion air temperature of 1000°C and oxygen concentrations (from left to right) of 21%, 8% and 2%, respectively (carbon dioxide as the dilution gas).

4. Clean Energy Conversion of Wastes

One of the challenges with the clean energy conversion of wastes is that the fuel composition is not uniform. The waste composition varies both spatially and temporally. Often the wastes contain large and variable amounts of moisture so that the traditional combustion and thermal destruction methods result in high levels of emissions and odors. The byproducts from the process can be often health hazardous. Any efforts to gain public confidence and achieve reductions in emissions must be based on engineering methods and concepts that provide fuel flexibility, and that the technology is adaptable for high ash, high moisture and low heating value fuels. The high temperature air combustion technology is ideally suited for the clean conversion of low -grade and waste fuels to clean fuels of uniform composition. It has also the potential for eliminating or alleviating the formation of dioxins and furans.

The principle involves converting wastes to gaseous fuels using high temperature air. The material is decomposed under high temperature conditions. The conditions are controlled so that the dioxins and furans are not formed. An example of the waste or low-grade solid fuel to clean gas conversion set-up is shown schematically in Figure 13. The waste in the chamber is converted to gas while the slag is tapped from the bottom of the chamber that can be used for the construction of roadbeds or in housing industry. The advantage of the system includes the production of clean gaseous fuel with high and variable amounts of moisture content in the waste fuel. The addition of steam with the high temperature air is beneficial for enhanced conversion of wastes to fuel and to promote hydrogen production. A careful tailoring of the amount of steam used with the high temperature air as well as the oxygen concentration levels in the air used is required for enhanced conversion of wastes to cleaner fuels. Careful design considerations can alleviate or minimize the expensive post treatment of the waste gases from the process. The technology has been shown to be instrumental for the clean conversion of some selected types of wastes while studies are in progress on other types of wastes.

Application of HPAC in gas turbines using gasified coal or waste fuels

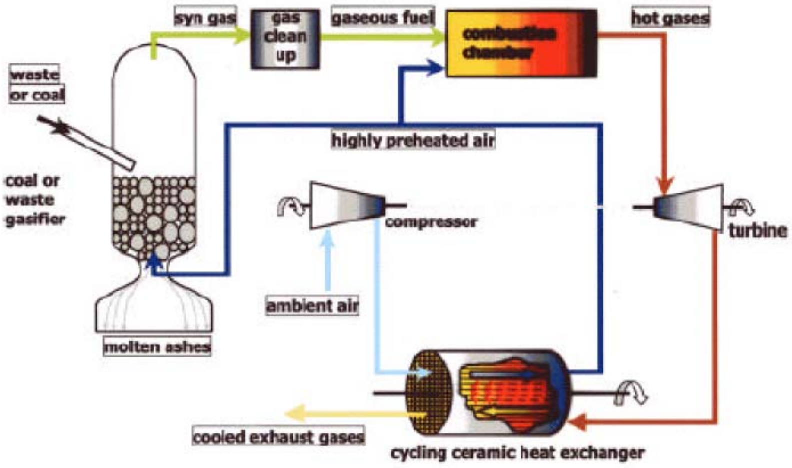


Figure 13. Application of high temperature air combustion technology for the conversion of wastes and low-grade fuels to clean gaseous fuels.

The high temperature air combustion technology can also be used in several other applications shown in Fig. 14. Some areas are currently in active stages of development while others are expected to follow in the near future. It should be pointed out that many of these areas require further basic research studies as well as some applied research for specific development and application [30-34]. The technical challenges involve determining the most suitable conditions for specific application since the chemical and physical characteristics are much different for each application. It is expected that many researchers and engineers from around the world will take active role to further develop this technology for specific applications.

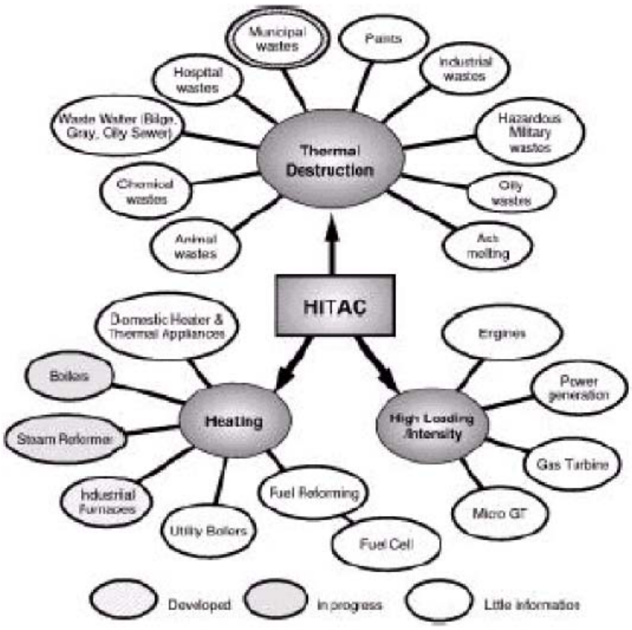


Figure 14. Near-term development efforts and potential applications of high temperature air combustion technology.

5. Challenges in High Temperature Air Combustion

Several demonstrations on several different kinds of furnaces (for example, heating treatment, melting, reheating) have shown significant energy savings, ranging from about 10% to 60%, with improved product quality. The challenge of using high temperature combustion is to tailor the flame thermal, chemical and fluid dynamic behavior with the specific application requirements. The conventional practice has been to develop a system for specific application. These days many additional conditions are imposed. The engineer must pay close attention to the life cycle costs, product disposal after useful life, environmental issues, health issues, legal issues, reliability, and simplicity for diagnostics and maintenance. The near term challenges for HiTAC include determining suitable conditions for specific application using various fuels. Systematic fundamental studies will provide optimum design guidelines for specific application. Some of the near term challenges include the following:

- Role of fuel property on combustion, emission and energy savings.
- Maximize/control the heat fluxes for a specific application.
- Effect of initial injection ‘puff’ of fuel or air injection from the burner on combustion and emission.
- Role of flow dynamics in the reaction zone on the flame chemical and thermal behavior. Also included here is the role of flow behavior on flame signatures and thermal time scales.
- Role of fuel injector design on fluid residence time, flame thermal signatures and emissions.
- Flame characteristics under flameless oxidation conditions.
- Health effects of flames under HiTAC conditions.
- Limits on the maximum achievable energy saving, pollutants reduction and down sizing of the equipment with HiTAC for specific application.

Systematic fundamental and applied studies in the future will allow one to gain insights into further applications of this technology. In addition it will provide a database for model validation and mathematical modeling in several application areas related to high temperature air combustion technology. The requirements for each application are much different. In the case of boiler the material temperature is some 200°C while in the case of ceramic industry the material temperature can be in excess of 1000°C. It is anticipated that additional applications will evolve from further R&D efforts on high temperature air combustion. Several efforts are now in place on the use of wastes and low-grade fuels. They have provided useful insights for practical applications.

Summary

Recent developments on high temperature air combustion have shown large energy savings, low pollution and downsizing of the equipment. The green flame color observed for propane flame and some other hydrocarbon fuels only occur under certain conditions. Hydrogen flame exhibited purple color under certain conditions. Fuel property has a significant effect on the flame thermal signatures. Some hydrocarbon fuels do not show the green flame color observed for the propane flame. The green color of propane flame increases with decrease in oxygen concentration and increase in air-preheat temperature. The observed yellow flame color was found to increase with increase in temperature and oxygen concentration. Blue flame color

predominates at air preheat temperature of up to 1000°C and O_2 concentration from 5 to 15%. The flame size increases with decrease in oxygen concentration and increase in air temperature. The flame standoff distance from the nozzle exit (ignition delay) was found to decrease with an increase in air preheat temperature. The emission of NO_x, although increasesing with an increase in temperature, was significantly lower at high temperature air combustion conditions as compared to the normal air. Flameless oxidation of the fuel (colorless flame) has been observed under certain conditions. Thermal uniformity of flame is significantly enhanced with high air preheat temperatures and low oxygen concentration of air. Flame signatures change significantly with change in air preheat temperature EGR, chemical composition of the dilution gas and O_2 concentration in the air. The heat flux distribution from flames with high temperature air is much higher and uniform than those obtained with normal temperature air. Data on the detailed flame structure as affected by the fuel property, fluid dynamics and high temperature chemical kinetics are urgently required for wider applications of this technology. The challenges of HiTAC flames for further applications of this technology have been presented.

High temperature air combustion technology has been demonstrated for energy conversion of selected types of wastes and low-grade fuels to clean gaseous fuels in an environmentally benign manner. The technology has potential for many types of wastes, including odors and ultra low heating value fuels.

Acknowledgments

The experimental facility used here was built and provided by NFK, Japan. Support of this project from NSF, NASA in the USA and NFK, Yokohama, Japan is greatly appreciated. Technical discussions with Mr. Toshiaki Hasegawa, Director of Basic Technology at NFK, are gratefully acknowledged.

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